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Structural health monitoring of the Santa Casa da Misericórdia Church in Aveiro

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***Abstract*—This paper presents a reduced visual impact structural health monitoring system, based on fibre Bragg gratings. This sensing network was developed for the church of *Santa Casa da Misericordia* of Aveiro and comprises 19 displacement sensors and 5 temperature sensors. All the sensors were custom made, according to the monitoring points' characteristics. The results obtained over the first year of monitoring are presented.**

***Index Terms*— Structural health monitoring; fibre sensors; Bragg gratings; optical sensors**

I. Introduction

The church of *Santa casa da Misericórdia* of Aveiro was built in the XVI and XVII centuries, and is an important part of the architectural and historical heritage of the city. Up to the date, this historical building has benefited from several restoring and consolidation interventions [1], the last ones dated from 1971 to 1975 and 1997.

The detection of some reasonably sized cracks in this historical structure drove the necessity to monitor some of the most important structural control parameters (deformation and temperature), in order to evaluate this structure stability.

Because this building is an important tourist attraction, the objective of this work was to evaluate this structure stability, maintaining a continuous record of the structural health of this historical building and simultaneously keeping the monitoring system almost invisible.

The sensors chosen were based in fibre Bragg gratings (FBG) technology. In addition to the advantages of being recorded in optic fibre, which make them transparent, small and lightweight, keeping the resistance and flexibility of the fibre, FBG sensors present a series of advantages which make them ideal for structural health monitoring [2], impact and damage detection [3] and cure monitoring of composite materials [4]. Because of their inherent wavelength response, FBG sensors are immune to electro-magnetic interferences and can easily be multiplexed for multi-point strain and/or temperature monitoring, in both surface or embedded sensing applications [5].

FBG sensors are absolute and linear in response, and the Bragg wavelength is determined by the well known Bragg phase-matching condition.

The wavelength shift of an FBG sensor, subjected to strain and temperature variations can be expressed as:

$$\frac{\Delta\lambda_B}{\lambda_B} = \left(1 - p_e\right)\varepsilon + \left(\alpha_\Lambda + \alpha_n\right)\Delta T \qquad (1)$$

Where p_e, ε, α_Λ , α_n and ΔT are the photoelastic constant, axial strain, thermal expansion coefficient, thermal optic coefficient and temperature shift, respectively.

For the sensing applications, p_e, α_Λ and α_n, are considered to remain constant. This way, the wavelength shift is considered to depend only on temperature and axial strain. To separate the strain signal from the temperature signal, the most common method consists in the use of two gratings.

In a preliminary analysis, the most important structural problems were identified and found to be at the central arch of the church. After that, the sensor's locations were defined, as shown in figure 1.

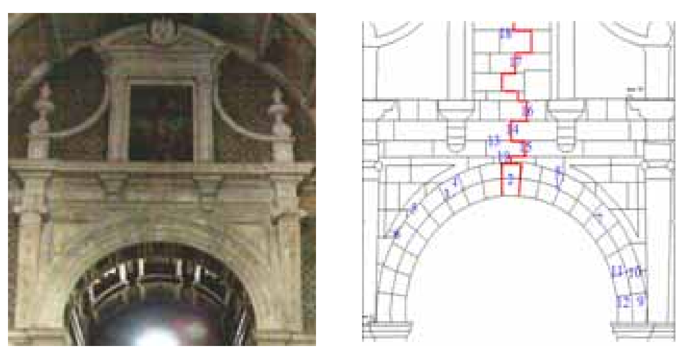

Fig. 1. Photo (a) and scheme (b) of the studied arch, containing the location of the sensors and critical zones.

II. Sensors

A. Sensor network

The sensor network comprises 19 displacement sensors and 5 temperature sensors strategically located in the points where

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the most important deformations were expected.

All the gratings were recorded in photosensitive telecommunications fibre using an automated interferometer system and exhibited high reflectivity. FBG sensors length was typically 2mm and the sensors total gage lengths varied from 140 to 300 mm with a working displacement range of ±0.2% of the length, allowing the measurement of both gap's aperture and close. The displacement and temperature sensors presented central wavelengths between 1535 and 1555 nm witch allowed the system to be wavelength multiplexed. The sensors network was constituted by 4 cables with 5 sensors each and one cable with 4 sensors connected to the interrogation unit using single mode optical fibre.

Two different groups of custom made sensors were used to monitor the gap evolution. The first group of sensors was used in plane regions and the second group of sensors was specially designed to the non-planar regions, overcoming some spatial restrictions imposed by the structure, as shown in figure 2.

B. *Sensor installation*

Besides the necessity to have minimum visual impact, this sensing system should stay away from any damage in the structure. In order to avoid the drilling and permanent damage of the stone, the sensors were bonded to the blocks using

(a)

(b)

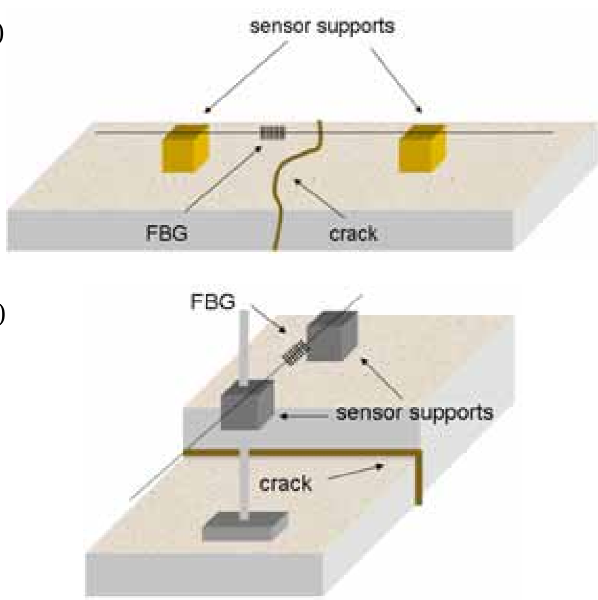

Fig. 2. Sensor designs used in the planar regions (a) and in the non-planar regions (b).

epoxy resin and after the sensors installation only the small size supports could be seen. The thermal expansion of the mounting arrangement was considered negligible.

The sensors were tensioned before installation to allow measuring both gap's aperture and closing. After all the sensors have been installed, they were connected to cables with transparent coated optical fibre, after that, the cables were attached to hidden zones of the structure and connected to the interrogation unit. The final task was to allow the sensors to move free and to settle. Following this, the central wavelengths were recorded to be the reference or start values for the monitoring process. Simultaneously, the temperatures near each temperature sensor were recorded using a thermocouple.

III. Results and Discussion

Data acquisition was made every two weeks, using an optical sensing interrogator unit from Micron-Optics Inc. (model # sm125) and a laptop. With this interrogation system, it is possible to have a displacement and temperature resolution of about 0.2µm and 0.1ºC, respectively. The temperature and displacement results for the most active regions are presented in figure 3.

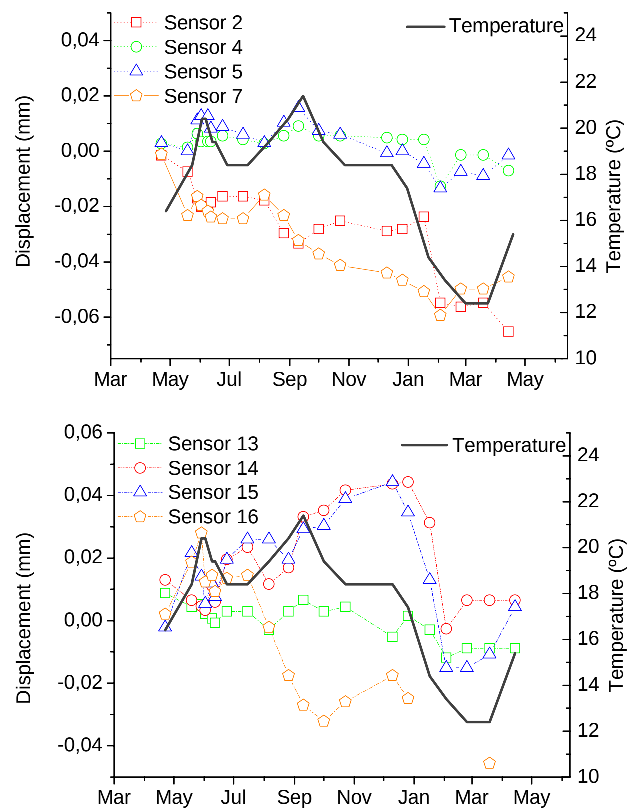

Fig. 2. Temperature and displacement data for two groups of sensors acquired since the beginning of the study.

Analyzing the displacement evolution over time, it is possible to see that all fissures present displacements due to the thermo-mechanical processes, caused by the temperature variations. Beside these variations, displacements caused by structural movements are noticed.

Looking closely to the evolution of some of the fissures, we can see that fissures number 4 and 5 present good stability over time, even with temperature variations. For these fissures, the total displacement after one year of monitoring can be considered negligible. On the other side, fissures 2, 7 and 15, presented, during the monitoring period, a clear tendency to close. This is an interesting observation, as we can see that the structure might be searching for its stability, adjusting itself adjusting itself over time, with some fissures enlarging their dimensions, and others decreasing. A longer monitoring period will allow to see clearer all the fissures trends and will help to identify which structure points need more attention.

In this figure it is also possible to identify sudden structural movements, such as the occurred in February monitored by sensor 2.

All the other sensors, presented essentially thermally driven movements, with slight effective displacements, as we can see by analyzing their evolution over time, and the first and last points of this graphs, where the temperature is almost the same, and where we can see some accumulated residual displacement.

IV. CONCLUSIONS

This paper described a structural monitoring system based on fibre Bragg grating sensors installed in the church of *Santa Casa da Misericórdia* of Aveiro. Two types of custom design sensors were used, allowing the monitoring of all the structure important points, without causing permanent damage to this historical building. Another important advantage of this system, considering the church is an important tourist attraction of the city, is that it is almost invisible, due to the reduced dimensions of the sensors and to the transparent fiber used.

Up to the date, this system has been used for discrete readings, every two to thee weeks, but the foundations for a more advanced remote structural monitoring system are installed.

During the fist year of monitoring, it was possible to observe that all the sensors showed displacements as result of thermo-mechanical processes, and some sensors revealed effective structural displacement.

Data is being analyzed in order to predict a possible danger situation for the structure and the information collected will be very useful when planning restoring and conservation interventions.

REFERENCES

[1] Santa Casa da Misericórdia de Aveiro, “Contextualização histórica da Misericórdia de Aveiro “, May, 2004

[2] Whelan M P, Albrecht D and Capsoni A 2002 “Remote structural monitoring of the Cathedral of Como using an optical fibre Bragg grating sensor system” *Proc. SPIE* 4694 242–52

[3] A. Takeda N, Okabe Y, Tsuji R and Takeda S 2002 “Application of chirped fibre Bragg grating sensors for damage identification in composites” *Proc. SPIE* 4694 106–17

[4] H. Lima, R. Ribeiro, R. Nogueira, L. Silva, I. Abe, J. L. Pinto 2007, “Continuous monitoring of setting and hardening of mortar using FBG sensors”, *Proc. SPIE* 6585

[5] D. Kersey, M. A. Davis, H. J. Patrick, M. LeBlanc, K.P.Koo, C. G. Askins, M. A. Putnam and E. J. Friebele, “Fiber grating sensors”, *J. Lightwaver*